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Massachusetts Institute of Technology
Lincoln Laboratory
P.O. Box 73
Lexington, Massachusetts 02173

LEAD SALT DIODE LASERS AND DEVELOPMENT OF TUNABLE SOLID STATE LASERS FOR REMOTE SENSING

SEMI-ANNUAL PROGRESS REPORT

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by

C. Freed and J. W. Bielinski

ABSTRACT

Extensive studies of the output characteristics of single quantum well lead-telluride lasers developed at the General Motors Research Laboratories were carried out. Threshold currents, output powers and line structures were measured as a function of temperature. Very low-current lasing thresholds, record high operating temperatures and over 30% tuning ranges were achieved. Excellent reproducibilities, good far-field patterns and reasonable linewidths (~500 kHz) were found.

Introduction

During the last several months, extensive studies of the output characteristics of lead-telluride quantum-well diode lasers were carried out. These lasers were developed and fabricated at the General Motors Research Laboratories (GMR) and loaned to MIT Lincoln Laboratory (MIT/LL) at no cost to the program, in the expectation that the results will mutually benefit all participants.

The multiplicity of data obtained both at GMR and MIT/LL clearly indicated that the lead-telluride quantum-well lasers achieved major improvements in tuning range, open-loop frequency reproducibility and mode stability, as well as significantly lower-current lasing thresholds and record high operating temperatures.

Brief Description of the PbTe Quantum-Well Diode Lasers

Molecular beam epitaxial (MBE) growth of $Pb_{1-x}Eu_xSe_yTe_{1-y}$ lattice-matched to PbTe substrates has been used to fabricate double heterojunction diode lasers, including the single quantum-well, large optical cavity (LOC) devices to be discussed in this report; PbEuSeTe is a new material recently developed at the General Motors Research Laboratories, which can be used to cover the 2.6 to 6.6 µm wavelength range.(1-3) Mesa stripe geometry diode lasers were fabricated(4) with stripe widths from 16 to 22 µm and the cleaved cavity lengths were typically 325 to 450 µm long. The PbTe quantum-well width, L_z, was varied in the sequence 300, 600, 1200 and 2500 Å in a series of otherwise similar growths. Strong quantum effects were observed for $L_z \leq 1200$ Å, and the shift in laser emission energy was in approximate agreement with that calculated from a

finite square well potential. Dale Partin reported in greater detail on the design and construction of these single quantum well PbEuSeTe diode lasers.(5) This report will concentrate on some of the observed output characteristics.

Operating Temperatures

Lasing was achieved at record high temperatures, 174K and 281K under cw and pulsed (~1 μs) operation, respectively.(5) These temperatures are well within thermoelectric cooling range.

Threshold Currents and Power Outputs

Lasing was achieved also at remarkably low threshold currents. At 13K the cw threshold current was only 2.1 ma for a 600 Å single quantum well laser(6) (less than the biasing current for many infrared detectors).

Figure 1 shows the cw threshold current and corresponding current density as a function of temperature for MBE-4, which was a single, 300Å quantum-well diode laser. At low temperatures lasing began at very low threshold currents on transitions between n=1 states. The increasing steepness of the threshold current at higher temperatures was probably due to the fact that at the higher temperatures a greater fraction of the electrons goes into pumping transitions between n=2 states. Notice that for n=2 state transitions there was a decrease in threshold current as one increased the operating temperature. Eventually a temperature was reached(5) (under pulsed conditions) at which the n=2 threshold current approximately equalled the n=1 threshold. Above this temperature the n=2 threshold current increased rapidly and the n=1 transition was no longer observed. This behavior of theshold currents was typical for other quantum well lasers too, and not just a unique characteristic of MBE-4.

Figure 2 shows the single ended output power of MBE-4, as a function of current. The maximum (multiline) output power of about 5 mw was obtained in the vicinity of 60K. The various colors indicate the power at several different temperatures.

It should be noted that 550 ma diode current corresponded to laser operation at 50 to 75 times threshold current between 77 and 20K, respectively. Occasionally at least we used cw current drives up to about 1A without catastrophic failure or deterioration.

Experimental Arrangements

Figures 3 and 4 show block diagrams of the experimental setups used to perform high-resolution measurements of the output spectra, linewidths, tuning rates, frequency reproducibility, and spatial characteristics of mode patterns.

The diode laser radiation was combined on a beamsplitter with that of a grating-tunable stable CO reference laser. The beatnote of the two lasers was detected and very high resolution measurements of linewidths and/or tuning rates were achieved by using a spectrum analyzer. In order to facilitate some of the measurements (e.g., linewidths and tuning rates), the diode lasers could also be frequency-offset-locked as described elsewhere[7] and illustrated in Fig. 4. A portion of the radiation was also deflected to a grating spectrometer in order to determine the spacings of longitudinal modes and lasing transitions.

Far Field Radiation Patterns

Detailed observation on the spatial characteristics of output radiation impinging on a scatter plate was accomplished and recorded with a very

sensitive and sophisticated TV-compatible infrared scanning camera and video recorder. This system, together with a rotatable K-mirror enabled us to obtain intensity distributions, along any arbitrarily chosen axis, as well as three-dimensional intensity distributions and equal intensity contour lines. We found that the far field radiation patterns remained remarkably unchanged for any value of current drive; this is demonstrated by Fig. 5 which shows intensity distributions of MBE-4 at 77K for nine current levels beginning at lasing threshold and up to nearly 50 times the current at threshold. After reaching full scale deflection on the most sensitive detection scale, the laser current drive level was adjusted to produce full scale deflections using successive steps of the scope display attenuator.

The spotsize measured on the scatter plate had a diameter of about 1.5 mm. A 2" diameter 2" focal length Germanium meniscus lens was used to focus the laser radiation onto the scatter plate which was placed 12 ft. from the collimator lens.

The magnified spot at the highest current drive (~46 times threshold) is shown in the top left corner of Fig. 5 together with the cross section applicable to the nine intensity distributions of Fig. 5.

The black lines in Fig. 6 show the lasing transitions at 100K operating temperature of MBE-2 which was also a 300Å single quantum-well diode laser. Lasing threshold was reached at about 100 mA and the laser started operating on a transition between n=1 states in the conduction and valence bands. Transitions between the n=2 states required higher currents as was clearly demonstrated in Fig. 6. Also notice that at 100K, for this laser

at least, there was a wide current range between n=1 and n=2 transitions at which no lasing at all occurred and the power output was zero.

The blue lines in Fig. 6 show the transitions at 90K operating temperature. Notice that at 90K lasing can occur simultaneously on transitions between n=1 and n=2 states, and there is no drop out of laser power as was observed at 100K.

The red lines in Fig. 6 show the lasing transitions at 77K. A careful inspection of the line structure at 77K will indicate the presence of longitudinal modes in the two transitions just above and below 1950 cm^{-1}. Since the typical spacing between adjacent longitudinal modes was in the vicinity of 2 1/2 cm^{-1}, a family of longitudinal modes within the same transition must appear visually very closely spaced because the vertical scale spans 1000 cm^{-1} on Figures 5-7. At 77K the longitudinal modes appeared consecutively as the current was increased or decreased in a monotonic fashion. Longitudinal modes may also occur simultaneously, especially at lower temperatures. Also note that nearly 6 cm^{-1} continuous frequency tuning with current was possible (e.g. in the transition at 1900 cm^{-1}).

Notice, however, that there were transitions both in the n=1 and n=2 group, which were spaced more than 10-15 cm^{-1} apart. At this time at least, the exact cause of these spacings is not known. It has been suggested[8] that the transition degeneracy may be due to strains in the crystal. Indeed, the transition structures became more complex at lower temperatures where more strains were likely to occur. As an example, Fig. 7 shows the transitions of MBE-2 at 60, 40, and 20K, respectively. Note

that all the transitions shown in Fig. 7 operate between n=1 states of the conduction and valence bands. The lasing threshold current for the n=2 transitions at these low temperatures would have to exceed the 550 ma current limit used in this set of measurements. Notice the closely spaced appearance of the set of longitudinal modes in the 1820 cm^{-1} transition at 60K in the vicinity of 310 ma current drive.

The color coded lines of Fig. 8 show the line structure of the other 300Å single quantum-well diode laser, MBE-4, at 110, 100, 77 and 20K, respectively. Figure 8 also illustrates the points just discussed; the occurence of n=1 and n=2 state transitions at the higher operating temperatures, and the absence of n=2 transitions and increased complexity of the line structure at 20K. Also notice, that by tuning both with temperature and current one can cover more than 700 cm^{-1}, i.e., over 30% tuning range with a single quantum-well diode laser.

Tuning Rates and Frequency Reproducibility

Two tuning rates were applicable both as a function of current and as a function of temperature. A relatively fast tuning rate could be discerned by drawing an average slope across the line structure. About an order of magnitude smaller tuning rates were applicable by tuning within a mode. The tuning rates within a mode were determined by measuring the change in the beat frequency against a fixed CO or against a second diode laser reference line, as either the current or the temperature was changed by a small amount.

Heterodyne beats against about 60 different CO laser transitions between 5.1 and 6.0 μm were obtained. Since the quantum-well laser

transitions between the n=2 states occurred at wavelengths shorter than 4.7 μm, heterodyning against a CO laser was no longer possible and a second quantum-well diode laser was used as a reference. It must be emphasized that in spite of the complex appearance of the line structures, the reproducibility of lasing frequencies was quite remarkable in comparison with any other conventional lead-salt diode laser we previously encountered. The beatnotes were reproducible week after week (for at least several months) by simply adjusting the currents and temperatures to the previously recorded values.

Table I shows typical tuning rates in GHz/ma as a function of either current at a fixed temperature, or as a function of temperature at a fixed current. The highest tuning rates were produced by temperature changes. As previously mentioned, the tuning rates within a mode were about an order of magnitude smaller than across transitions. Smaller tuning rates were caused by current changes. Notice, however, that in the 300Å quantum-well lasers even the smallest tuning rate, which occurred within a mode, was about 700 MHz/ma, i.e., 700 kHz/μa. Thus the diode laser current supply must have very low noise and ripple, much less than 1 μa peak, in order to avoid spurious frequency modulations.

Measurements of Linewidths

The high current-tuning rate (~1 MHz/μa) encountered during these experiments necessitated the design and construction of a new, ultra low noise power supply. In the narrow-band mode (used for manual tuning) the noise was not measurable with any of the equipment available to us. We estimated that the combined (power supply plus measuring devices) peak 60

Hz ripple did not exceed 0.3 μv; however, in the wide-band mode (used for external modulation and frequency-locked operation) a small, but clearly observable white noise (without any spectral features) was observed.

Figure 9 shows spectrum analyzer displays of two beatnotes, one for MBE-2 at 20K and the other for MBE-4 at 77K. The vertical scales are logarithmic with a 10 db/cm calibration; the horizontal frequency scale is 10 MHz/cm. The dotted lines are computer generated Lorentzian profiles with 500 kHz full widths at half maximum (FWHM) power. Flat, white noise spectra 40 and 46 db below the respective Lorentzian peaks were also added to the computer generated dotted profiles in order to correct for the noise floor of the measuring system. Note that both pictures were taken with the diode lasers operating in a He-compressor driven closed-cycle refrigerator; however, since the diode lasers were frequency-offset-locked to the CO laser, the beatnotes appeared very stationary and stable for any length of time, regardless of compressor vibrations.

The approximately 500 kHz FWHM beatnotes shown in Fig. 9 are (to the best of our knowledge) the narrowest linewidths obtained from lead-salt tunable diode lasers operating in a commercial (CTI) closed cycle refrigerator and with a commercial (LAI) temperature controller, but using power supplies and feedback circuits designed and constructed at Lincoln Laboratory. However, the 500 kHz linewidths shown in Fig. 9 are probably an order of magnitude broader than estimated from the Schawlow-Townes formula (which equated $n_{sp}(1+\alpha^2)\equiv 1$)[9]. Undoubtedly, there was at least some contribution to the linewidths, shown in Fig. 9, which was due to (white) noise of the power supply (which was used in the wide-band mode

in order to provide frequency-locked operation). However, there were at least preliminary indications that most of the broadening was due to adjacent longitudinal modes. Further clarification of this very important problem area will have to depend on the results to be obtained in the next phase of our investigations.

Conclusions

Experimental evidence has shown that the PbTe quantum-well diode lasers achieved:

- very low lasing thresholds (2.1 ma at 13K)
- record high operating temperatures (174K cw, 281K pulsed)
- over 700 cm^{-1} (>30%) tuning with a single laser
- excellent reproducibility
- good far-field patterns
- reasonable linewidths (~500 kHz)

Although the measurements answered many questions, puzzling results also remain. Perhaps foremost of these relate to the detailed physics which determine the spacings of the various transitions. Further investigation of linewidths is also necessary. It is believed, however, that even the partial results outlined above indicate that quantum-well structures achieved a real break-through in the state of the art of lead-salt diode lasers.

References

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4. D. L. Partin, R. F. Majkowski and C. M. Thrush, J. Appl. Phys. 55, 678 (1984).

5. D. L. Partin, "Single Quantum Well Lead-Europium-Selenide-Telluride Diode Laser," Device Research Conference, Santa Barbara, Ca, (1984), to be published in Appl. Phys. Lett.

6. D. L. Partin, private communication.

7. C. Freed, J. W. Bielinski, and W. Lo, Programmable, Secondary Frequency Standard Based Infrared Synthesizer Using Tunable Lead-Salt Diode Lasers, SPIE Proc. 438, 119 (1983).

8. B. Lax, private communication.

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TYPICAL TUNING RATES IN GHz/mA AS FUNCTIONS OF DIODE CURRENT AND TEMPERATURE

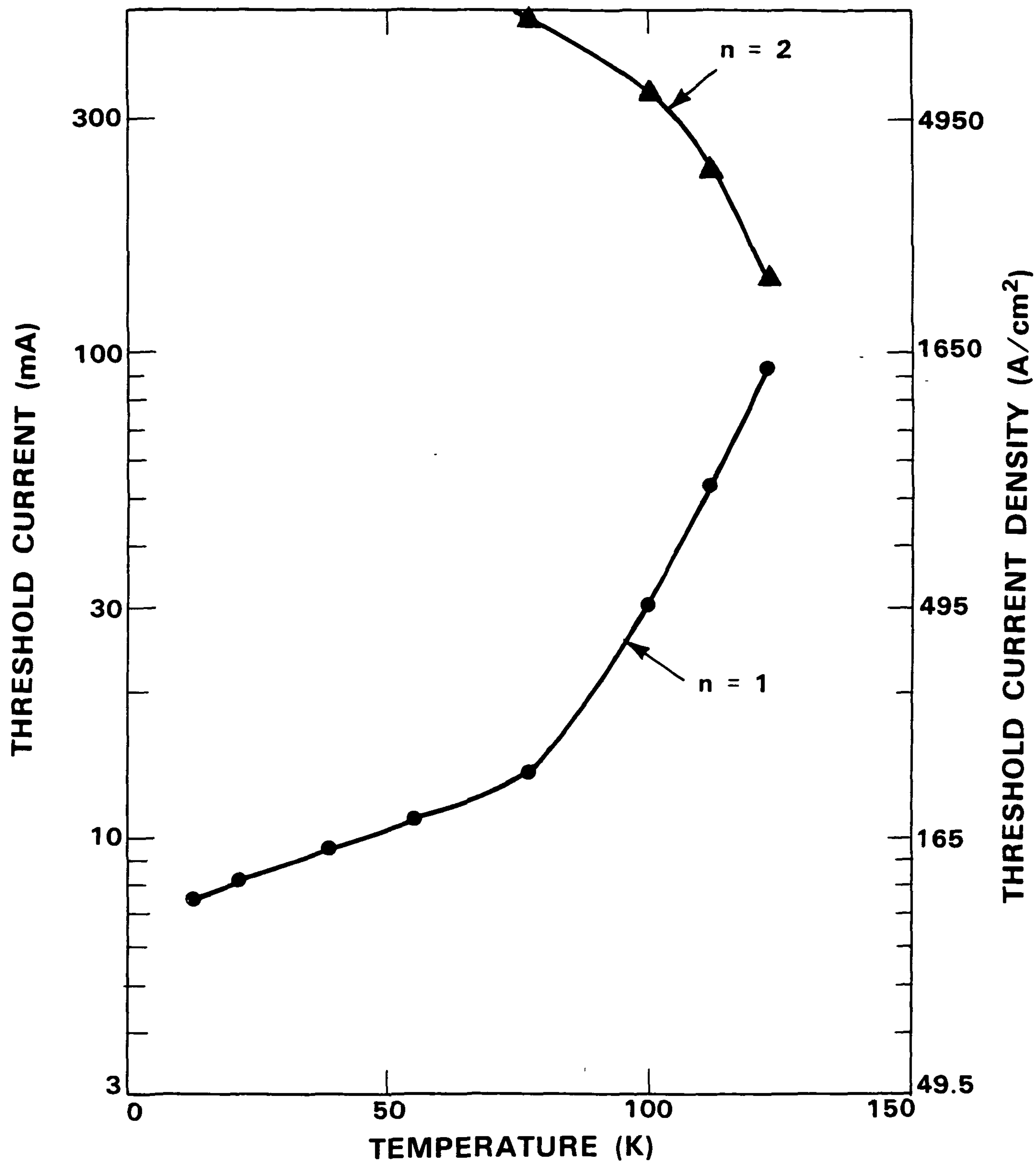
LASER DIODE	f(I); $T \simeq 77$ K		f(T)	
	WITHIN MODE	ACROSS TRANSITIONS	WITHIN MODE	ACROSS TRANSITIONS
MBE-2 (300 A)	0.70 - 1.5 1.25 (n = 2)	8.9	16.6 (200 mA; 77 K)	121 (250 mA; 20-77 K)
MBE-4 (300 A)	0.75 - 1.1 1.67 (n = 2)	12.4	13.6 (67 mA; 77 K)	126 (250 mA; 20-77 K)
MBE-5 (600 A)	0.25	3.5		

- OVER 700 cm^{-1} ($\sim$2 μm) TUNING WITH A SINGLE LASER
- NEARLY 6 cm^{-1} CONTINUOUS TUNING WITH CURRENT IN A SINGLE MODE

TABLE I

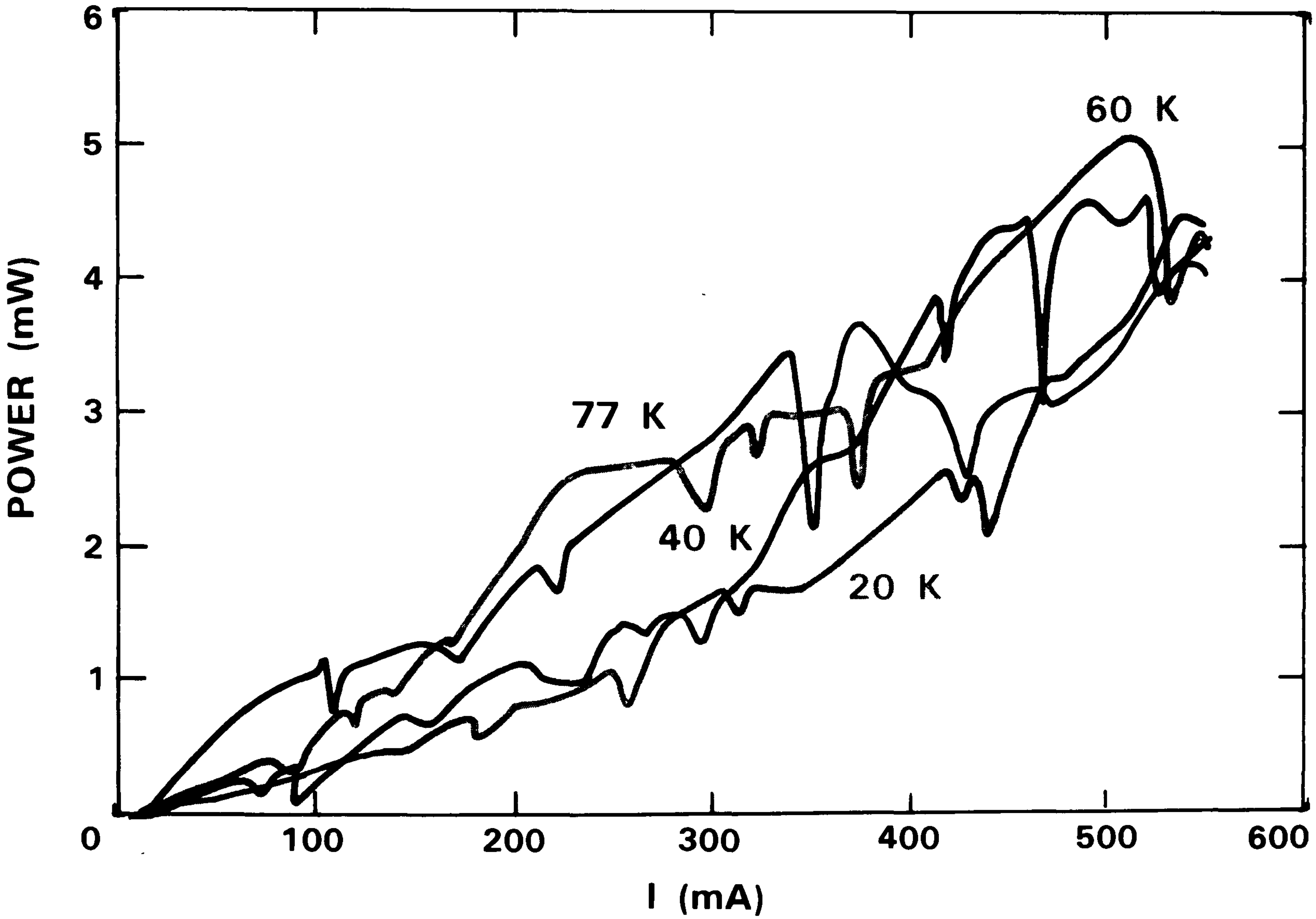
141432 N

THRESHOLD CURRENT/DENSITY OF MBE-4



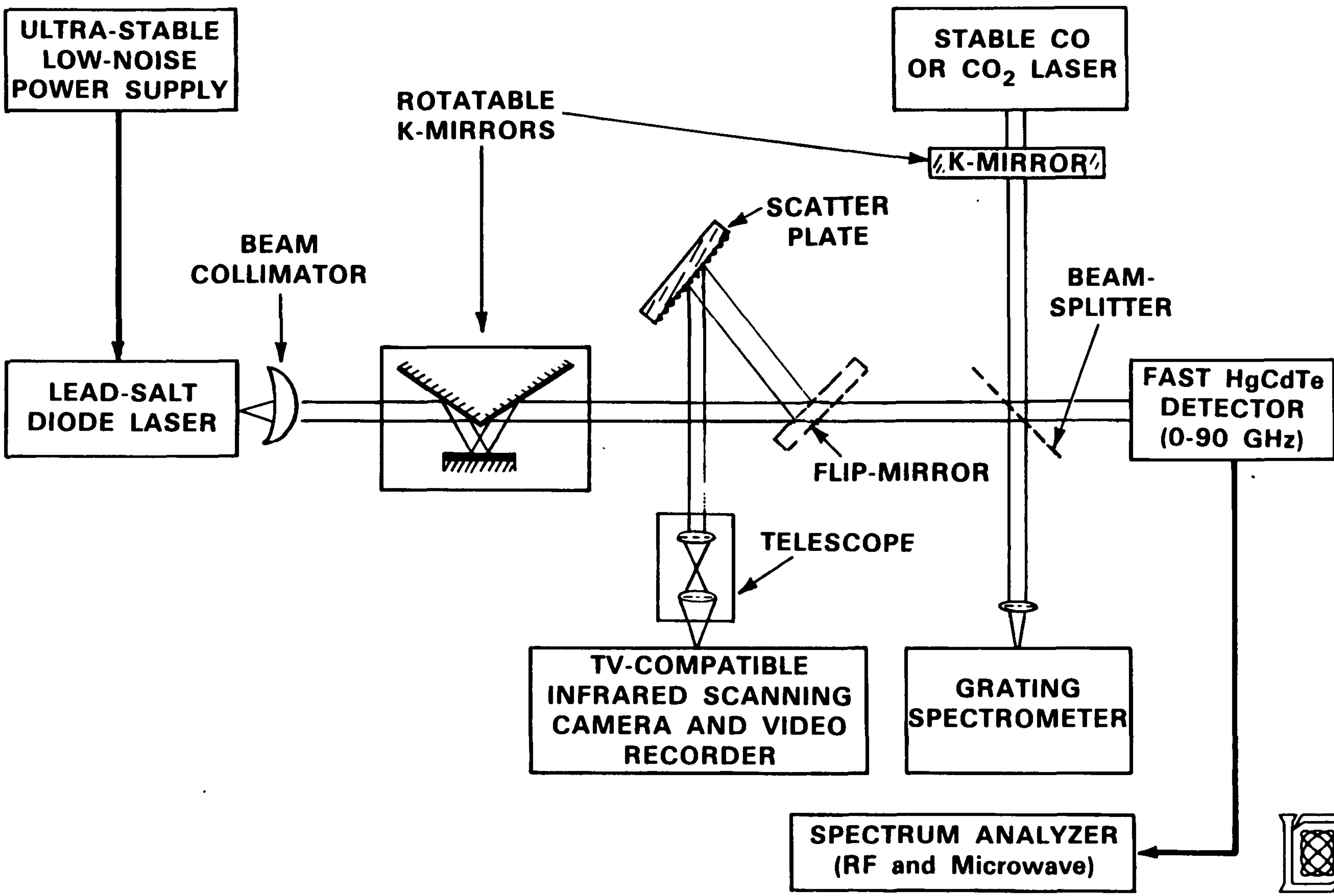
141420-N

SINGLE-ENDED OUTPUT POWER OF MBE-4

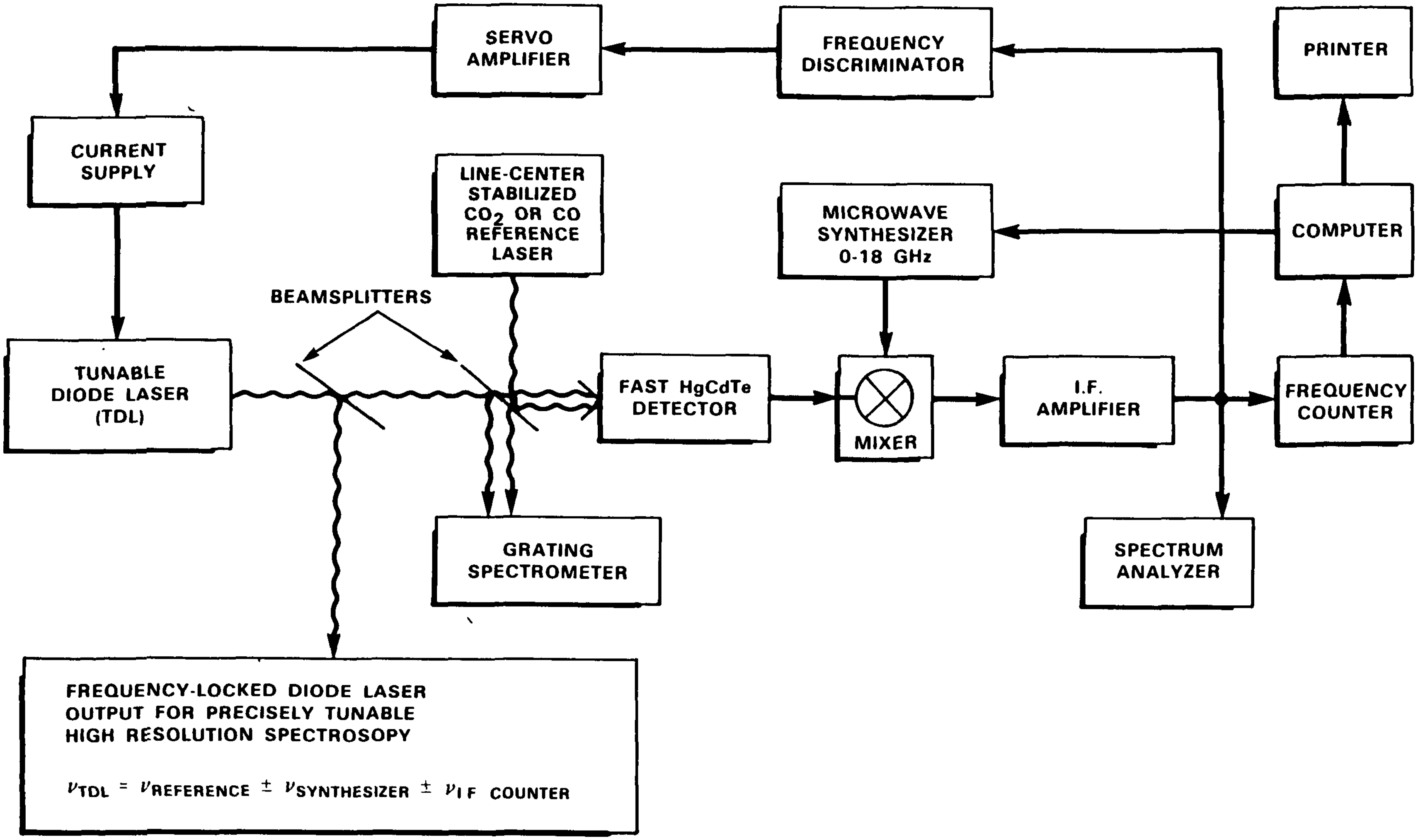


141425 N A,B C

BLOCK DIAGRAM FOR THE HIGH RESOLUTION TESTING OF THE OUTPUT SPECTRUM, TUNING RATE, AND SPATIAL CHARACTERISTICS OF LEAD-SALT DIODE LASERS



136312-N



BLOCK DIAGRAM OF A PRECISE, CONTINUOUSLY TUNABLE INFRARED FREQUENCY SYNTHESIZER

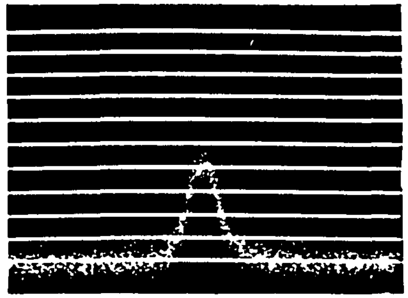
124207 N 01

FOCUSED FAR FIELD PATTERN OF MBE-4

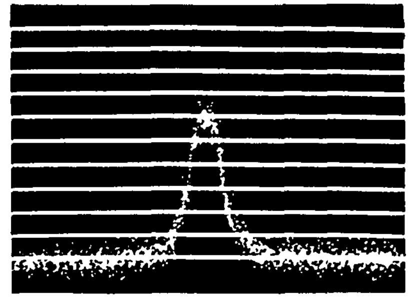
SPOTSIZE ≃ 1.5 mm; MAGNIFICATION ≃ 70

538.8 mA; ≃ 46.1 × THRESHOLD

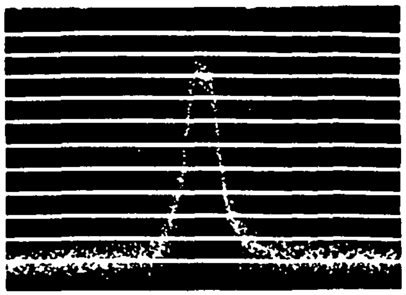
11.7 mA; ≃ 1 × THRESHOLD



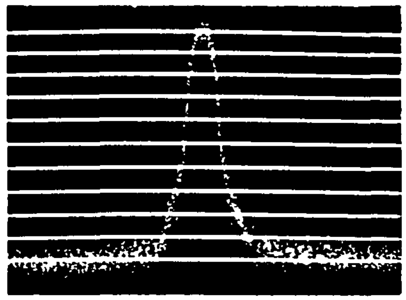
13.2 mA; ≃ 1.13 × THRESHOLD



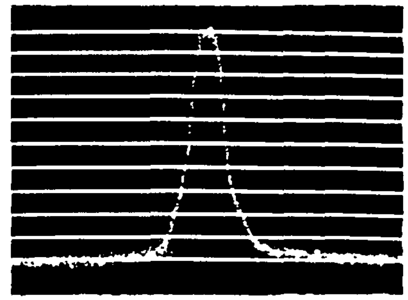
14.72 mA; ≃ 1.26 × THRESHOLD



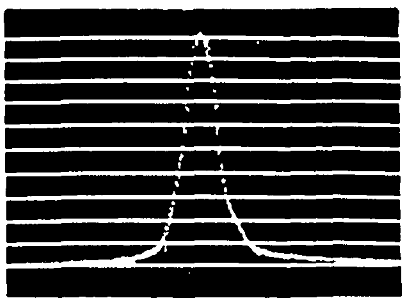
16.4 mA; ≃ 1.4 × THRESHOLD



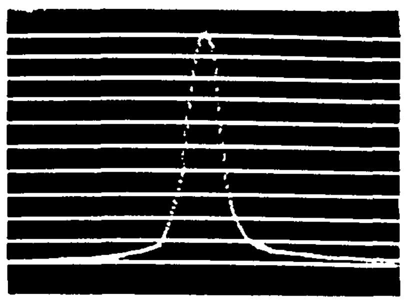
18 mA; ≃ 1.54 × THRESHOLD



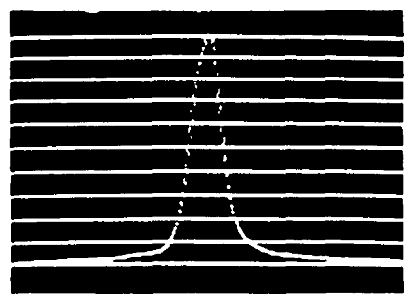
25.8 mA; ≃ 2.21 × THRESHOLD



83.9 mA; ≃ 7.17 × THRESHOLD

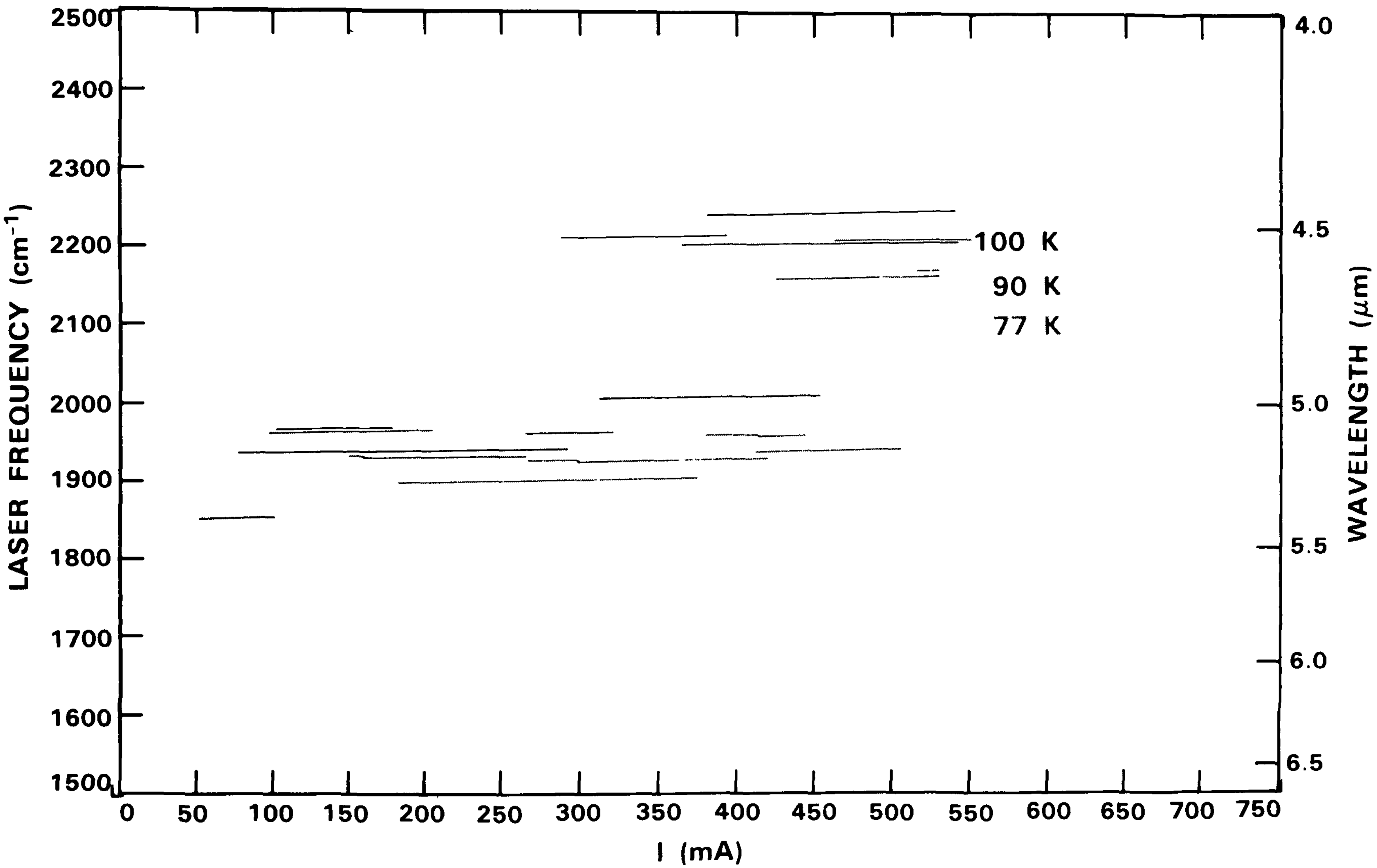


278.6 mA; ≃ 23.8 × THRESHOLD

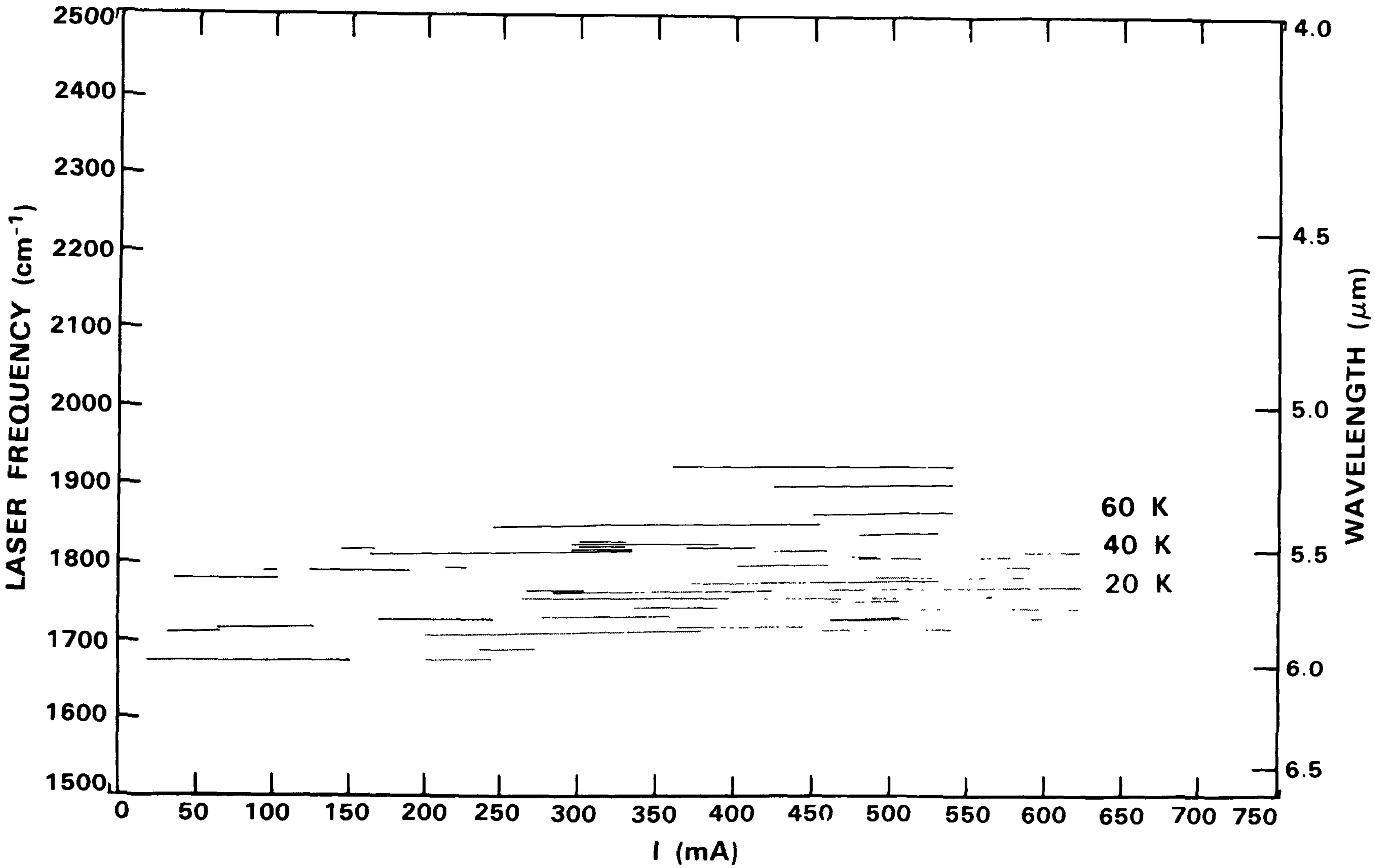


538.8 mA; ≃ 46.1 × THRESHOLD

LASING TRANSITIONS OF MBE-2

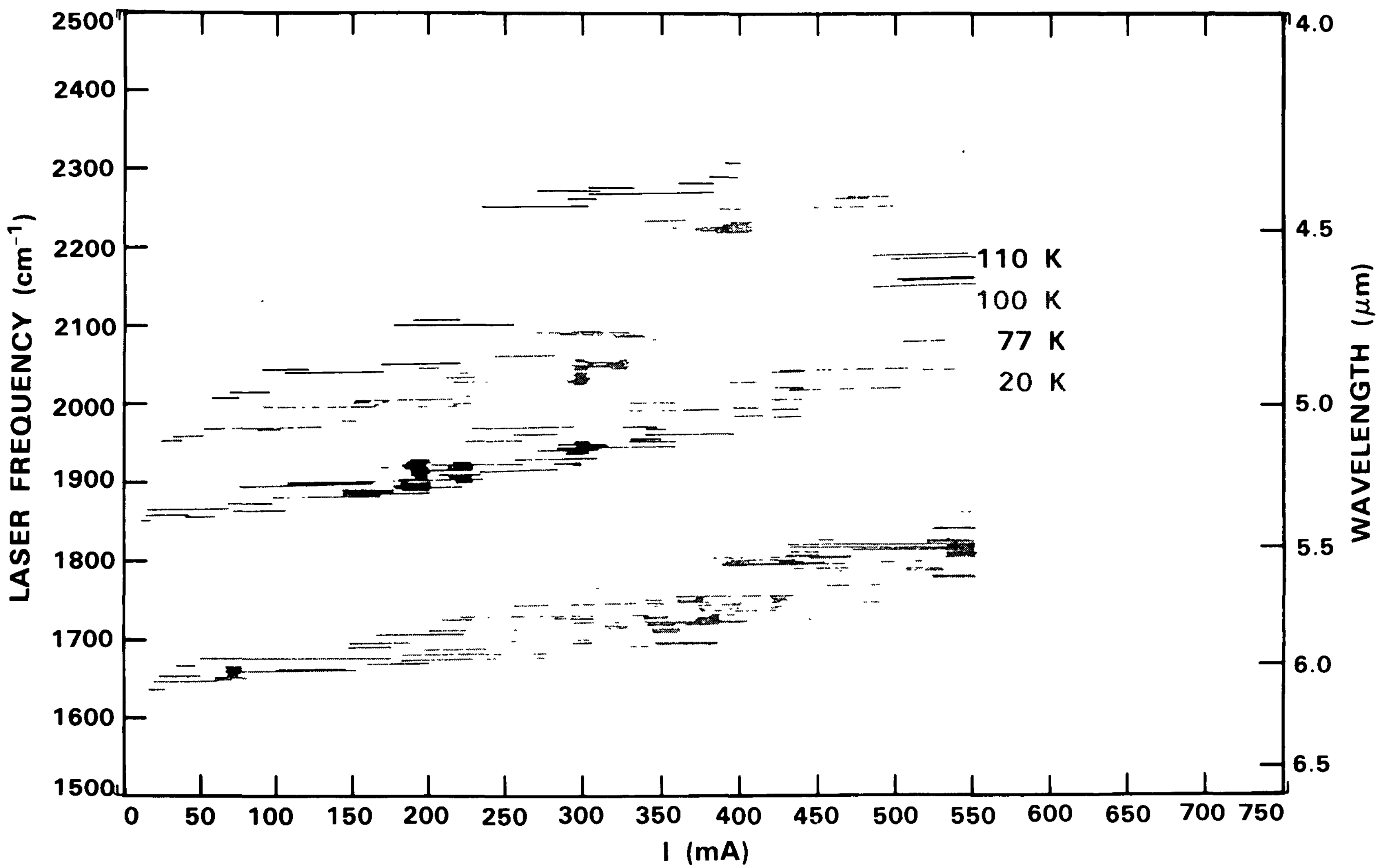


LASING TRANSITIONS OF MBE-2



141428 N A B

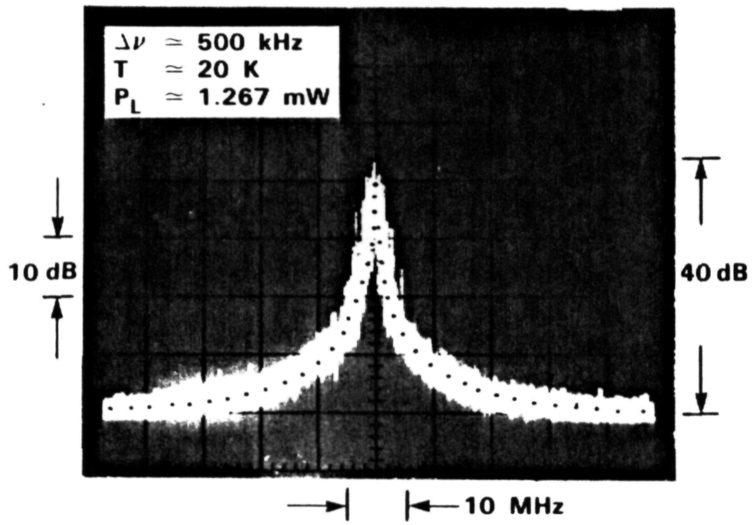
LASING TRANSITIONS OF MBE-4



141427 NABC

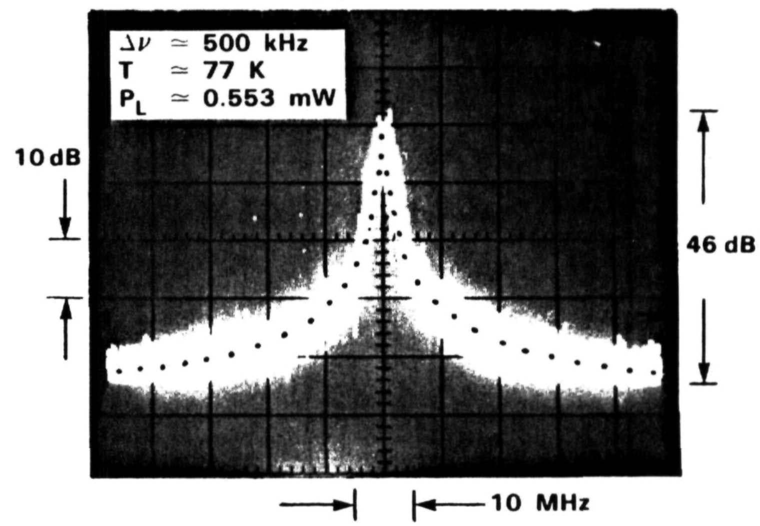
BEAT-NOTE SPECTRA OF 300 Å SINGLE QUANTUM-WELL LASERS
(10 kHz Filter; Lorentzian Fits)

MBE-2



$P_T \simeq$ 1.298 mW
I $\simeq$ 0.317 mA
$\nu \simeq$ 1714.49 cm^{-1}

MBE-4



$P_T \simeq$ 0.916 mW
I $\simeq$ 0.094 mA
$\nu \simeq$ 1865.01 cm^{-1}

141434-R